A New Technique in Milling Steel

By JAY ANTENEN ME IV

EVEN JUST A FEW YEARS ago at the beginning of this war, mechanical engineering handbooks, such as Kent's, list the optimum cutting speed for milling S.A.E. 1050 steel to be 75 to 95 feet per minute. This was with milling cutters of ordinary high-speed tool steel as it was not considered feasible to use sintered-carbide tools even though they were available at that time. Late in 1942, however, what has amounted to a revolution in milling technique was begun, and we now find very hard steel being milled with speeds and metal removal rate that were unheard of before then. Typical practice now is shown in Figure 1 where a forged aircraft-landing gear strut of extremely hard and tough S.A.E. 4140 molybdenum steel is being straddle milled at 440 feet per minute. The milling cutter is composed of a solid Meehanite, high strength cast iron body with ten sintered-carbide tips brazed on. Metal is being removed at such a rate that disposing of the quantity of chips becomes a problem in itself.

The cutting tips are ground with what is known as a *negative radial rake angle*. The radial rake angle of a milling cutter is defined as "the angle by which the face of the tooth is displaced back of the radial line drawn from the center of rotation to the cutting edge." If the face is displaced back of the radial line the rake angle is called *positive* and if forward, is *negative*. There is a definite relation between this angle and the cutting force required at the tip of the tool. This relation is shown in the curve of Fig. 2 where it is seen that the larger the rake angle, the less force necessary. It would seem desirable to use a large rake angle, but this is seldom done because the tip is weakened and will heat up too easily by reason of the small mass. From the graph it would also be reasonable to assume that if a *negative* rake angle would be employed a still larger cutting force and hence power would be necessary.

In 1942, M. E. Merchant and N. Zlatin made a study of rake angles of milling cutters. With a special machineability dynamometer they designed especially for the purpose they were able to measure the cutting force involved. The effect of cutting speed upon the cutting force was observed using different radial angles. Their data was used to draw the curves in Fig. 3. They show that with an ordinary 10 deg. positive rake angle there is a definite rise in the cutting force as the cutting speed is increased. However, a cutter ground with a negative rake angle showed, strangely enough, the opposite tendency with all other conditions remaining the same. With increased cutting speeds the cutting force dropped off until at very high speeds, it was even less than the seemingly more efficient positive rake angle.

More recent research along these lines indicates that the curve for positive rake does not cross but merely closely approaches the curve for negative rake. This is shown in Fig. 4.

But this phenomena is not easily explained. The investigators mentioned before have a theory based on further analysis of the friction forces and shearing angles at the tip which indicates that this falling off of the cutting force is due in large part to the higher rate of heat dissipation because

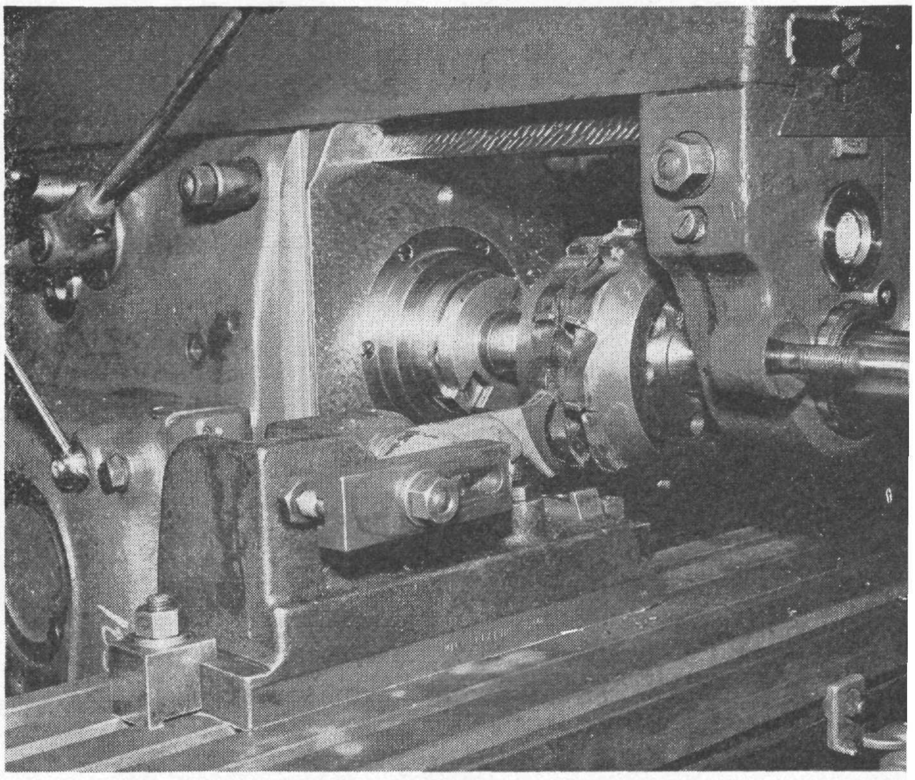
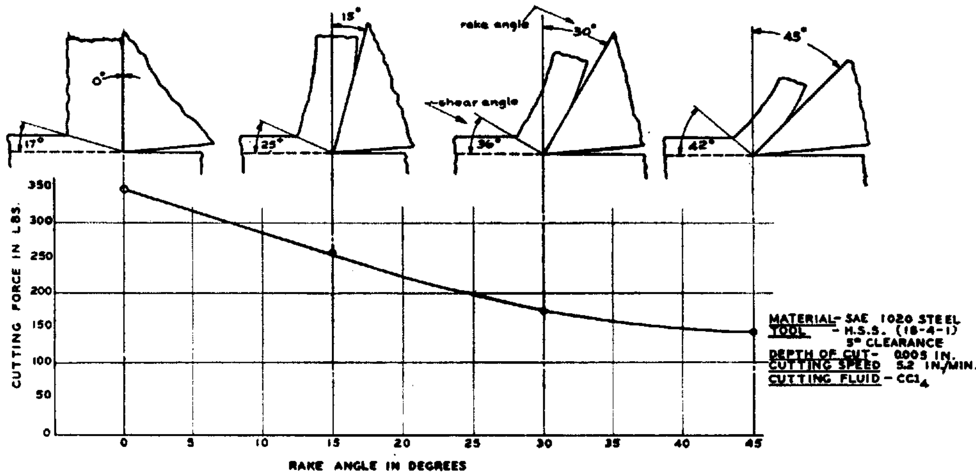


Figure 1—A Modern Milling Operation

Courtesy Mechanical Engineering



Courtesy Mechanical Engineering

Figure 2—Curve showing relationship or rake angle and cutting force.

of the higher cutting speeds and the resultant high tooth and chip temperatures. A good part of the power necessary in cutting has been found to be caused by the friction force necessary to slide the chip along the face of the tool. Furthermore it is Dr. Merchant's assumption that there is an actual adhesion between the chip and the face of the tool and movement of the chip is accomplished by actually shearing a thin layer of metal as it slides along. If the shear strength of the metal could be lowered in some way, much less force would be necessary. It seems probable that this must be one of the secrets of the lowered cutting force at high speeds as the shear strength of metals rapidly decreases as the temperature is raised.

The photomicrographs shown in Fig. 5 were taken in the laboratories of the Cincinnati Milling Machine Company with a camera which would stop the motion of the chip relative to the tool in only 0.000002 seconds. Here, the remarkable improvement in chip formation at high speeds with negative rank angles is easily seen. Photograph (a) was made of a carbide-tipped face-milling cutter having 10 deg. positive rake angle and a 3 deg. clearance angle, and operating at a cutting speed of 140 feet per minute. These were the usual conditions that milling cutters formerly were operated under. The cutter in (b) was the same as in (a) except that the 10 deg. positive rake was reversed to a 10 deg. *negative* rake. At the same 140 feet per minute speed, the effect is certainly very bad. The shear angle has gone down to only 6 deg. and the chip has piled up against the face of the tooth causing extremely high cutting force.

In (c) is photographic evidence of the effect of increasing the cutting speed of this same 10 deg. negative rake angle cutter to 780 feet per minute. Here, because of the high temperatures and lower coefficient of friction that obtain under these conditions, the chip flows more readily over the surface and is much thinner than before. The shear angle has correspondingly gone up to 20 deg. causing an additional decrease in the cutting force.

A large increase in power required is obviously necessary when these high cutting rates are reached. Milling machine manufacturers have redesigned many of their models with this in mind and now provide machines with much heavier parts and larger horespower motors to drive them.

The aircraft industry in particular has found the new technique welcome as many elements in

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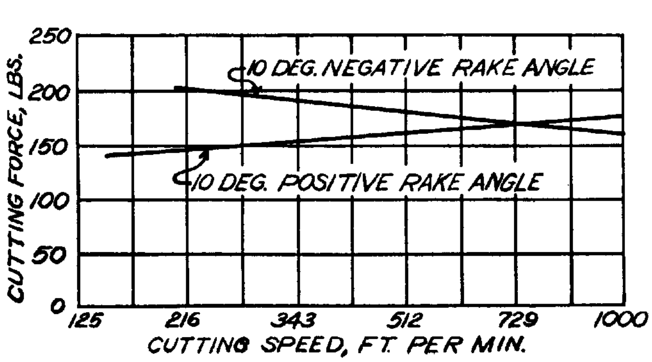


Figure 3

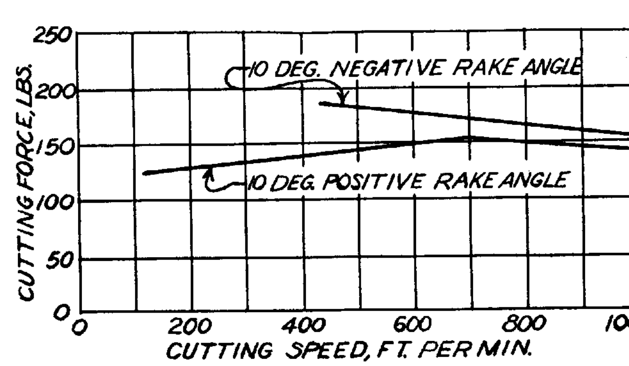
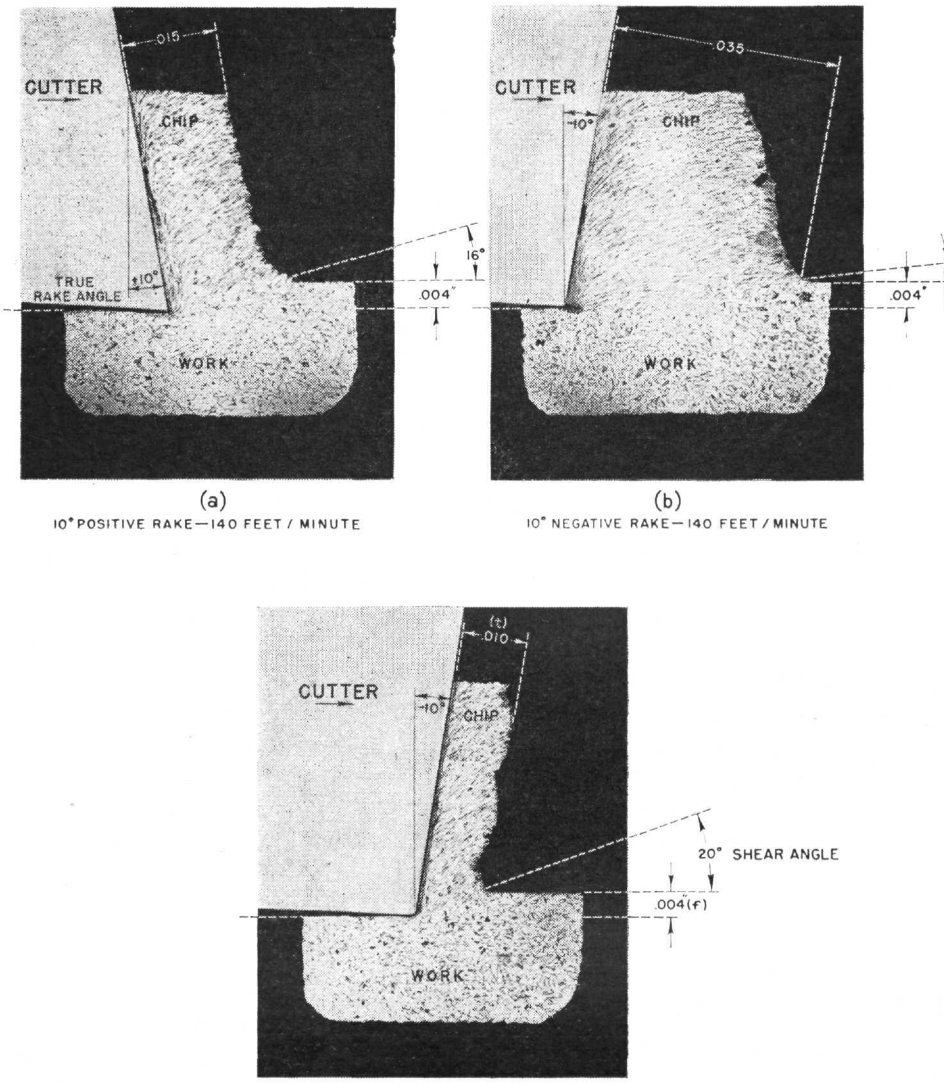


Figure 4



(a)
10° POSITIVE RAKE—140 FEET / MINUTE

(b)
10° NEGATIVE RAKE—140 FEET / MINUTE

(c)
10° NEGATIVE RAKE — 780 FEET / MINUTE

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an airplane are highly stressed and so made of high strength alloy steel which is vary hard and difficult to machine. Most of the heat generated by the fast cutting action is carried away by the red-hot so the piece being milled is not so apt to be warped by heating and cooling. It has been found that milling cutters with negative rake angles will allow higher production, better finish, and less distortion of the work pieces, all of which play a large part in producing an air force which will help win this war.

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Fig. 5—Photomicrographs of the cutting action at the tip of the tool.

Courtesy Mechanical Engineering